BBC RD 1973/21

BBC

RESEARCH DEPARTMENT

1969
THE QUEEN'S AWARD TO INDUSTRY

REPORT

DIGITAL TRANSMISSION CODES: preliminary investigation of HDB3 and related ternary codes for broadcast signal distribution

T.A. Moore, B.E., M.Eng. Sc.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION September 1973

BBC RD 1973/21
UDC 621.394.14

DIGITAL TRANSMISSION CODES: PRELIMINARY INVESTIGATION OF HDB3 AND RELATED TERNARY CODES FOR BROADCAST SIGNAL DISTRIBUTION

T.A. Moore, B.E., M.Eng. Sc.

Summary

An investigation has been carried out to assess the implications for broadcast signal distribution of the use of HDB3 as the proposed customer interface code in the Post Office digital communication network. HDB3 is a three-level transmission code with no d.c. component and with a bound on the maximum number of successive equi-level symbols. These two characteristics are important since a.c. coupling may then be employed in the transmission path and virtually continuous timing information can be extracted from the coded signal.

The properties of related transmission codes, including the class of alphabetic (or block) codes were also investigated, in view of the likely adoption of one of these (4B 3T) by the Post Office as a line transmission code at the higher bit rates.

The effect of transmission-code digit errors on the decoded binary sequence was studied and suitable error correction schemes are outlined. An experimental HDB3 codec was constructed, primarily to demonstrate the feasibility of such transcoding at bit rates up to the order of 120 Mb/s, using commercially available integrated circuits.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

(EL-79)

DIGITAL TRANSMISSION CODES: PRELIMINARY INVESTIGATION OF HDB3 AND RELATED TERNARY CODES FOR BROADCAST SIGNAL DISTRIBUTION

September 1973

BBC RD 1973/21
UDC 621.394.14

DIGITAL TRANSMISSION CODES: PRELIMINARY INVESTIGATION OF HDB3 AND RELATED TERNARY CODES FOR BROADCAST SIGNAL DISTRIBUTION

T.A. Moore, B.E., M.Eng. Sc.

1. Introduction

The proposed general form of the Post Office digital communications network is shown schematically in Fig. 1. The interface code carries the signal from the source to a multiplexer and again from a demultiplexer to the receiver. The line code is used for long-distance transmission and is intended to operate at a 120-140 Mb/s bit rate. Interconnections joining the lower-order multiplexes may also be made directly, operating at lower speeds and using a suitable code.

Both the interface and line codes belong to the general class of 'transmission codes', that is, they have properties which render the signal more suitable for transmission over conventional links than the binary signal generated by the source. As such, they generally have a small low-frequency content with a null at zero frequency (or d.c.), thereby permitting a.c. coupling in the link, and also ensure that level transitions are never absent for more than a short period in order to facilitate the regeneration of the timing waveform at each repeater in the link.

The Post Office proposes to use, for the customer interface code, HDB3, which has achieved wide acceptance in Europe as a transmission code; there is less certainty regarding the choice of the line code for trunk routes but this may well be 4B 3T. Both these codes, and the related codes discussed in this report are ternary (i.e. three level), d.c. free, and maintain a bound on the maximum number of successive symbols of the same level.

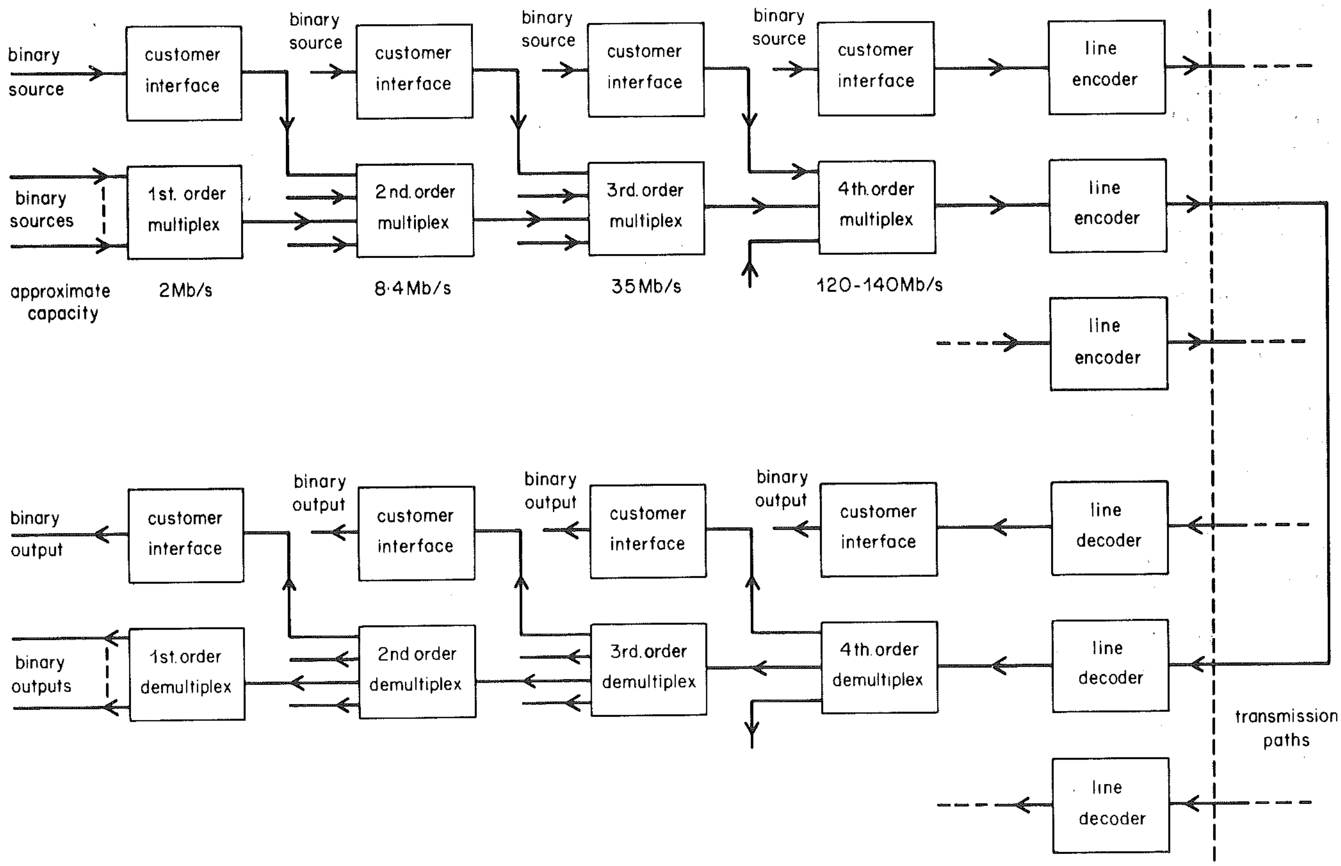


Fig. 1 - Post Office digital communications network schematic

(EL-79)

The investigation described in this report was carried out to assess the implications of using these codes for broadcast signal distribution. In particular the susceptibility of the decoded binary signals to transmission errors was examined. Since the customer will be expected to provide the digital signals to the network in interface code form, an experimental codec was constructed to confirm the general feasibility of conversion between binary and HDB3 codes at bit rates as high as 120 Mb/s. This rate corresponds to the maximum to be used in the first experimental digital transmission cable system in the U.K.

2. Digital transmission code requirements

The desirable properties for digital transmission code may be summarised as follows.

(a) Spectrum: The spectrum of the coded signal should have a null at zero frequency to avoid the need for d.c. coupling at any point in the transmission path.

(b) Power Content: To minimise power feeding requirements the total signal power should be as low as possible for a given peak-to-peak signal swing.

(c) Timing Information: In order that virtually continuous timing information be included in the transmitted signal, the maximum number of successive symbols of the same level should be restricted.

(d) Bit-sequence independence: The transmission code should be able to accept any binary sequence as the input.

(e) Symbol Rate: The transmission symbol rate must be low enough to allow the signal to be transmitted within the available bandwidth; on the other hand the number of code levels should be low enough to provide an acceptable error performance in a given noise environment.

(f) Error Extension: For the purposes of this report, this is defined as the mean number of errors in the decoded binary sequence per transmission error; this quantity should be as low as possible. (When the symbol rate differs in the transmitted and binary streams the ratio of symbol error rates will be the product of the error extension and the symbol frequency ratio.)

(g) Error Monitoring: Some form of in-service error-monitoring facility is desirable in a transmission code.

(h) Framing: In block codes the relative position of a symbol within a block must be known; hence block synchronisation must be maintained at the decoder. In addition, since the detection of framing loss is generally accomplished by monitoring the occurence of certain illegal symbol combinations, it is important to ensure that the block synchroniser is not easily 'fooled' by errors in transmission.

(j) Instrumentation: The design of the encoder, decoder and error monitor associated with a given code should be realisable without undue difficulty using commercially-available devices.

3. Description of transmission codes for broadcast-signal distribution

3.1 Code types

The transmission codes under consideration for reasons given in Section 1 may be divided into two classes, referred to as high density bipolar and alphabetic, or block, codes. The three levels of the ternary transmitted are denoted as +, 0 and –.

3.2 High-density bipolar codes

In a bipolar signal a binary zero is coded as 0, and a binary one alternately as + or –; this alternate mark inversion (a.m.i.) process ensures that no d.c. component exists in the signal. To obtain a higher timing content the bipolar signal may be modified to a high-density bipolar signal by replacing long strings of zeros in the encoded signal with filling sequences whose presences are indicated by the inclusion of marks disobeying the a.m.i. rule (referred to as violations). Among such codes are HDBn, where n = 2,3 .... and refers to the permitted maximum number of successive zeros. A variant of HDBn is CHDBn; C stands for compatible, since it is possible with this class of codes to design a decoder which is independent of n. Finally, the code B6ZS proposed in the USA[1] also belongs to the class of high-density bipolar codes.

Denoting a (bipolar) mark obeying the a.m.i. rule by B and a violation by V, then in HDBn, a binary one is coded as B, and a binary zero as O; however, any sequence of (n + 1) zeros in the binary signal is coded as the filling sequence

(n+1)

B O ....OV or
O O ....OV

also comprising (n + 1) symbols.

The choice of filling sequence is determined by the stipulation that successive *violations* be of alternate polarity, so that B, having the same polarity as V, is inserted in place of the first zero if V could not otherwise be a violation of opposite polarity to the previous violation. The following example, with n = 3, illustrates the procedure:

BINARY
1100 0001 0010 0001 1111 0000 0000 1011 0001

BIPOLAR
+–00 000+ 00–0 000+ –+–+ 0000 0000 –0+– 000+

HDB3
+–00 0–0+ 00–+ 00+– +–+– 000– +00+ –0+– 000+

The example given above in the lower line illustrates, for n = 3, that the HDBn sequence contains at most n successive zeros and that two adjacent marks are never of the same polarity.

With CHDBn the filling sequence of $(n + 1)$ symbols is of the form

OO .... OOOV or
OO .... OBOV

With B6ZS, 6 successive zeros are replaced by the sequence OVB OVB.

The symbol rate of these modified bipolar coded signals is equal to the bit rate of the incoming binary signal.

With decreasing n, the timing content of the HDBn and CHDBn signals increases, as does the average power. Because of the additional storage required, instrumental complexity for coding and decoding increases as n is increased. HDBn codes are slightly less complex than CHDBn to instrument. Because it has only two possible filling sequences (compared to four in the cases of HDBn and CHBn), B6ZS is easier to instrument than the comparable HDB5 or CHDB5 codes.

3.3 Alphabetic codes

With alphabetic codes the incoming binary signal is divided into blocks of a certain length, and to each binary block there is assigned a block of ternary symbols. In general, the transmission symbol rate will differ from source bit-rate; it is, of course, essential at the receiver to correctly frame the ternary blocks. The choice of ternary block transmitted is dependent on the running digital sum (or digital integral) of the coded signal. A transmission null at d.c. is achieved since the code tends to choose a ternary word in such a way as to reduce the running digital sum if it exceeds some set value or to increase it if not; thus the time integral is caused to vary within a fixed range about this set value.

The simplest alphabetic code is pair-selected-ternary in which both the binary and ternary words are 2 digits long[2]. In general, however, because of the number of ternary combinations available, the ternary symbol rate can be less than the source bit-rate. Two codes,[3,4] which convert blocks of 4 binary digits into blocks of 3 ternary symbols are 4B 3T and MS 43: they are described by their code books shown in Tables I and II. These codes are attractive from bandwidth considerations since their symbol rate is three quarters that of a comparable bipolar signal.

TABLE I: 4B 3T Code Book

4-bit Binary word \ Running digital sum	1, 2, 3		4, 5, 6
0000	+ + +		− − −
0001		0 + −	
0010		− 0 +	
0011		+ − 0	
0100		0 − +	
0101		+ 0 −	
0110		− + 0	
0111	+ 0 0		− 0 0
1000	0 + 0		0 − 0
1001	0 0 +		0 0 −
1010	+ + −		− − +
1011	− + +		+ − −
1100	+ − +		− + −
1101	+ + 0		− − 0
1110	0 + +		0 − −
1111	+ 0 +		− 0 −

Timing information may be extracted from the encoded signal since the maximum number of successive symbols of the same level is a fixed number when alphabetic codes are used: this equals 6 and 5 in the cases of 4B 3T and MS 43 respectively. The block framing may be checked and corrected because, in the preferred codes, loss of block synchronisation gives rise to occasional inadmissable ternary combinations (such as 000 in the case of 4B 3T).

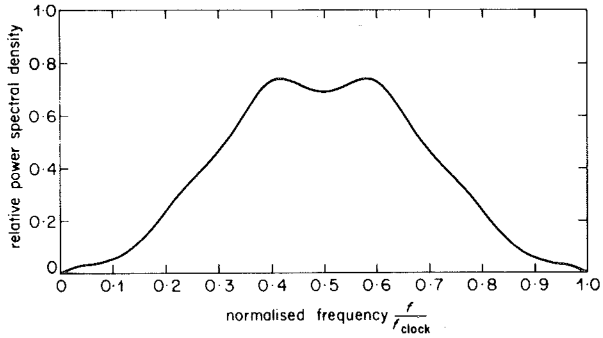


Fig. 2 - HDB3 Power Spectrum

4. HDB3 Properties

4.1. Spectrum

The power spectrum of an HDB3 signal is roughly similar to that of a bipolar signal which, for a random symmetric binary source*, is sinusoidal, peaking at half symbol rate and with spectral nulls at d.c. and symbol rate. Calculation of the spectral density of a code may be carried out by treating the coded sequence as a Markov process[6] and by suitable manipulation of the transition probability matrix[5]. Fig. 2 shows the computed spectral density under conditions of a random symmetric binary input*; the pulses in the encoded sequence are assumed to be much narrower than the clock period (i.e. mathematically they are taken to be Dirac delta functions)**.

*A random symmetric source is one in which the probability of a binary 1 or 0 at any time instant is independent of the previous transmitted sequence; in addition a 1 or 0 is equally likely.

**For pulses which are mathematically Dirac delta functions, the spectrum is periodic in frequency (with period equal to the clock frequency); this periodic continuation is not shown in the diagrams. The power spectral density of the transmitted signal depends upon the selected pulse shape; it may be computed by multiplying together the power spectral density using Dirac delta functions (given above) and that of the selected pulse shape.

TABLE II: MS 43 Code Book

4-bit Binary word \ Running digital sum	1		2,3		4
0000	+++			−+−	
0001	++0			00−	
0010	+0+			0−0	
0100	0++			−00	
1000		+−+			−−−
0011			0−+		
0101			−0+		
1001		00+			−−0
1010		0+0			−0−
1100		+00			0−−
0110			−+0		
1110			+−0		
1101			+0−		
1011			0+−		
0111		−++			−−+
1111	++−			+−−	

The power content of an HDB3 signal is 11% greater than that of a comparable bipolar signal, and arises because of the injection of filling sequences where the bipolar signal contains long strings of spaces.

4.2. Error performance

We now consider the susceptibility of the decoded binary signal to HDB3 transmission errors.

Assuming the simplest form of decoder (in which each violation and the third previous symbol in the received sequence are set to zero), a single transmission error can cause up to three errors in the decoded binary sequence. For example the sequence 1101, coded as + – 0 + would become + 0 0 + if the second symbol were in error, and would then be decoded as 0000, introducing three errors. The appendix, Section 10.1, gives details of the effects of various transmission errors on the binary decoded signal. It may be seen that an isolated transmission error can cause (depending on the encoded signal) 0, 1, 2 or 3 errors in the decoded signal. These errors are, however, localised within a block of five symbols; two errors, spaced four clock periods apart are possible, as are three errors in a block of four consecutive bits.

For the decoding technique outlined above, CEPT* studies have shown that the error extension (as defined in Section 2) would lie in the range 1·7 to 2·0 and that the adoption of a different decoding strategy (detecting the triplet 00V and setting V, together with the third previous symbol, to zero) would reduce the extension to the range 1·3 to 1·7.

Error monitoring is possible by detecting whether successive violations in the received signal alternate in polarity; two successive violations of the same polarity imply an error on transmission. It is therefore possible to detect the occurrence of an error between two deliberate (i.e. encoded) violations in the transmitted signal; for a random symmetric input binary source these occur on average once every thirty symbols.

4.3. Instrumentation

An experimental HDB3 encoder and decoder (including provision for error monitoring) were constructed with emitter-coupled logic devices (using a family with a 2 ns propagation delay). Satisfactory operation was achieved at clock rates of up to 120 MHz; no insuperable instrumental problems should arise in the construction of a model for operational service.

The logic design is given in the Appendix, Section 10.2.

*CEPT - Council of European Postal and Telecommunication Administrations - is an international organisation for co-operation between European Postal and Telecommunication Authorities.

5. Properties of other codes

5.1. Spectra

As n is increased, the spectral properties of the HDBn and CHBn modified codes approach those of a pure bipolar code; B6ZS has slightly more energy at half symbol rate[1].

Because of the small range to which the running digital sum is confined in the case of the alphabetic codes under consideration, transmission nulls exist at d.c. (and at clock frequency). For the alphabets shown in Tables I and II*, the spectra (assuming a random symmetric binary input) of 4B 3T and MS 43 are shown in Fig. 3. The spectra were computed as described in Section 4.1 for HDB3.

5.2. Error performance of alphabetic codes

The error performance of a block code is dependent on the choice of alphabet; the error extension is equal to the average distance (in the Hamming[8] sense) between the binary words corresponding to the transmitted sequence, and the decoded sequence in error. Since decoding is by means of a 'look-up' table, a single transmission symbol error does not effect more than a single binary word (corresponding to the ternary word affected by the transmission error).** It is expected that the error extension could be kept below half the binary word length, (the value achieved for a random alphabet allocation).

Error monitoring for alphabetic coding can be of a relatively crude form; an error is presumed to have occurred if, at the decoder input, the running digital integral leaves its allowable range. However, a more elaborate form of error monitoring, involving re-encoding at the decoder and

*For a random symmetric binary input the spectra are, in fact, independent of the first columns of Tables I and II, i.e. of which binary 4-bit words are assigned to the various blocks. It may be noted that all ternary combinations (except 000) are used.
**It has been estimated that the use of a scrambler to reduce word-patterning effects under conditions of a steady input signal would increase the spread of errors in the decoded binary signal caused by isolated transmission errors.

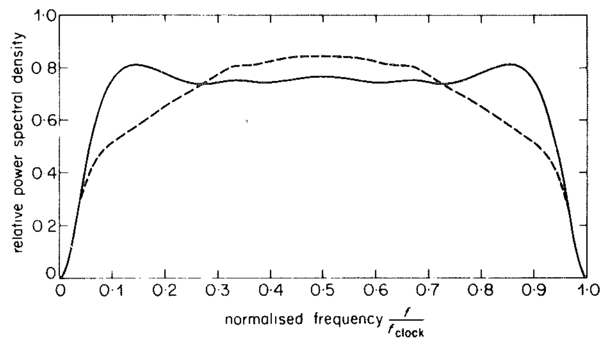


Fig. 3 - 4B 3T and MS 43 Power Spectrum
——— *4B 3T* - - - - - - *MS 43*

comparing the re-encoded and received signals, is also possible; since this would detect an anomalous choice of alternative ternary blocks it would respond to a greater proportion of errors as soon as they occur, and may therefore be preferred.

A complication can arise with alphabetic codes since transmission errors can cause a spurious detection of loss of word synchronisation. (Loss of synchronising is detected by the occurrence of 'illegal' ternary word combinations, such as 000 in the case of 4B 3T). In addition, loss of word synchronisation can cause the error monitor to register falsely. Distinguishing between loss of synchronising and a high transmission error rate is generally not easy at the decoder.

6. Error correction

With the HDB3 code, an isolated transmission error can cause a number of errors in the decoded binary signal, as described in Section 4.2, separated by at most four clock periods; with 4B 3T and MS 43 codes the errors in the decoded signal caused by a single transmission error are, by the nature of the codes, confined to a block of four bits. The similarity of short burst errors in binary code to the errors caused by isolated transmission errors suggests that methods employed for burst error correction would also be suitable for dealing with the effect of (isolated) transmission code errors. In particular, any error correcting code designed to correct bursts of 5 or more (4 in the case of 4B 3T and MS 43) would be suitable for dealing with the effects of isolated errors on transmission*.

7. Conclusions

The investigation described in this report was carried to assess the likely effect on broadcast signal distribution of the choice of HDB3 as the interface code, and the probable choice of 4B 3T as the line code in the proposed Post Office digital signal network.

The nature of the code is such that isolated transmission errors give rise to short burst errors in the decoded binary signal. This suggests the use of burst-error-correction techniques when the HDB3 signal is subject to an error-rate above the acceptable level without correction. However, it is likely that, as the interface code will be used only for relatively short-distance transmission on co-axial cables, the error-rate will be low enough on circuits using HDB3 alone to give an acceptable error performance without advanced error protection techniques.

Similarly with alphabetic codes, isolated transmission errors again give rise to short bursts of errors in the decoded signal, provided that the signal is transmitted as encoded (i.e. not 'scrambled'); this implies that, for error correction purposes, a system capable of dealing with bursts of 4 or more errors would be suitable. Many such methods have been proposed, and in general it is possible to convert any single error-correcting code to a burst error-correcting code by a process of interleaving.

Although attractive as a transmission code from bandwidth considerations, an alphabetic code such as 4B 3T suffers from the disadvantages (compared to bipolar and its derivations) that word synchronisation must be maintained at the receiver and that no simple form of reliable error monitoring is possible; in addition, it could be difficult to distinguish between the effects of synchronising loss and errors incurred on transmission. It is hoped that practical experience will be gained from a proposed Post Office experimental high-bit rate link in the South of England in 1975.

Finally, the encoding and decoding processes for HDB3 were found to be instrumentally feasible using conventionally available devices.

*If it is required to correct for errors caused to the line-coded signal, it is not necessary to employ burst-error correction methods to the lower order bit-rate signals. Since bit interleaving is employed in the multiplexers, a short burst-type error in the decoded line signal is converted, by the demultiplex action, into a number of single errors in some of the channels which comprise the line signal.

8. Acknowledgements

The author wishes to thank Mr. Uphill of the Post Office Research Department and Messrs. Schickner and Zick of the Post Office Telecommunications Development Department with whom helpful discussions have been held.

9. References

1. CROISIER, A. 1970. Compatible high-density bipolar codes: an unrestricted transmission plan for PCM carriers. *IEEE Trans. Commun. Technol.* **COM-18**, 3, 2, pp. 265 – 268.

2. SIPRESS, J.M. 1965. A new class of selected ternary pulse transmission plans for digital transmission lines. *IEEE Trans, Commun. Technol.*, **COM-13**, 3, pp. 366-372.

3. JESSOP, A. 1968. High capacity PCM multiplexing and code translation. *IEE Colloquium on PCM.* Paper No. 14. *IEE Colloquium Digest* 1968/7.

4. FRANASZEK, P.A. 1968. Sequence-state coding for digital transmission. *Bell. Sys, Tec, J.* 1968, **47**, 1, pp. 143 – 157.

5. YASUDA, H and INOSE, H. 1970. Direct calculation method for power spectra of pulse sequences by means of transition probability matrices. Electronics and Communications in Japan, 1970 **53-A**, 11, pp.366-372.

6. BALAKRISHNAN, A.V. 1968. Communication theory. New York, McGraw-Hill, 1968, Ch. 2.

7. CROISIER, A. 1970. Introduction to pseudo ternary transmission codes. *IBM J. Res. Developm.*, **14**, 4, pp. 354 – 367.

8. HAMMING, R.W. 1950. Error detecting and error correcting codes. *Bell Syst. tech J.*, 1950. **XXIX**, 2, pp. 147 – 160.

10. Appendix

10.1. Effect of HDB3 transmission errors on the decoded signal

The following table details the effect of various transmission errors on the decoded binary sequence, for a wide range of input signals. The simplest form of decoder is assumed, in which any mark disobeying the alternate-mark-inversion rule is set to zero, together with the third previous symbol. *Denotes which encoded symbol is affected by a transmission error, $\underline{1}$ or $\underline{0}$ denote an error in the decoded binary sequence. Errors involving two-level transitions (+ to −, − to +) are not considered; they are generally much less frequent than errors involving single-level transitions.

The previous bipolar mark, and the previous violation are both assumed to have been negative (−).

Encoded Signal	Received Signal	Decoded Signal	Note
+ +* 0 0 +	+ − 0 0 0 +	1 1 0 0 0 $\underline{1}$	3
+ − + 0* 0 +	+ − + − 0 +	1 1 $\underline{1}$ $\underline{1}$ 0 $\underline{1}$	5,1,3
+ − + 0* 0 +	+ − + + 0 +	$\underline{0}$ 1 0 0 0 0	8,6
+ − + 0 0 +*	+ − + 0 0 0	1 1 $\underline{1}$ 0 0 0	9,5
+ − + −* + 0 0 +	+ − + 0 + 0 0 +	1 $\underline{0}$ 1 $\underline{0}$ 0 0 0 0	2,7,6
− +* 0 0 0 +	− 0 0 0 0 +	$\underline{0}$ 0 0 0 $\underline{1}$	2,3
+ 0* 0 0 +	+ − 0 0 +	1 $\underline{1}$ 0 0 $\underline{1}$	1,3
+ 0 0* 0 +	+ 0 − 0 +	1 0 $\underline{1}$ 0 $\underline{1}$	1,3
+ 0 0 0* +	+ 0 0 − +	1 0 0 $\underline{1}$ $\underline{1}$	1,3
+ 0 0 0* +	+ 0 0 + +	$\underline{0}$ 0 0 0 0	8,6
+ 0 0 0 +*	+ 0 0 0 0	1 0 0 0 0	9
+ − +* 0 0 −	+ − 0 0 0 −	1 1 $\underline{0}$ 0 0 $\underline{0}$	2,4
+ − +* 0 0 0 −	+ − 0 0 0 0 −	1 1 $\underline{0}$ 0 0 0 $\underline{0}$	2,4
+ − + 0* 0 −	+ − + − 0 −	1 1 $\underline{0}$ $\underline{1}$ 0 $\underline{0}$	1,4,6
+ − + 0* 0 −	+ − + + 0 −	$\underline{0}$ 1 1 0 0 1	8,6
+ 0 − + 0* −	+ 0 − + + −	1 0 1 1 0 1	8,6
+ −* 0 +	+ 0 0 +	$\underline{0}$ $\underline{0}$ 0 $\underline{0}$	2,4,6

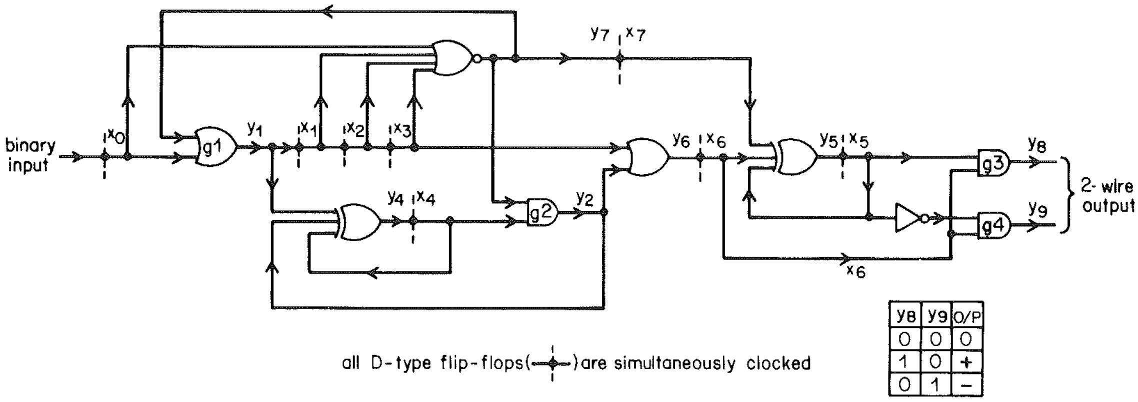
Notes:

1. A space is changed to a bipolar mark.
2. A bipolar mark is changed to a space.
3. A mark which was a violation is interpreted as a bipolar (A.M.I.) mark.
4. A bipolar (A.M.I.) mark is interpreted as a violation.
5. A bipolar mark in a filling sequence is interpreted as an (ordinary) bipolar mark.
6. The third previous symbol to a wrongly-interpreted violation is set to zero.
7. A bipolar mark in a filling sequence is interpreted as a violation.
8. A space is changed to a mark disobeying the A.M.I. rule, and interpreted as a violation.
9. A violation is changed to a space.

10.2. HDB3 encoder and receiver design

(i) Encoder logic

The encoder logic is shown in Fig. A1. If a row of four zeros in the output sequence (x_0, x_1, x_2, x_3) is detected a mark (violation) is inserted by means of y_7, through gate g_1; this is done three clock periods later. In addition, the variable x_4 decides whether a filler (the bipolar mark at the beginning of the filling sequence) is inserted, gated through g_4 by y_7 (the four-zero detector). y_6 (or x_6) then determines whether a mark or space is transmitted. x_5 determines the sign of the output marks; it changes at every bipolar mark. The two-wire output is formed from x_6 and x_5 by gates g_5, and g_6; the three-level output signal would be formed by an analogue subtraction of y_9 from y_8.



y_8	y_9	O/P
0	0	0
1	0	+
0	1	−

Fig. A1 - HDB3 Encoder Logic

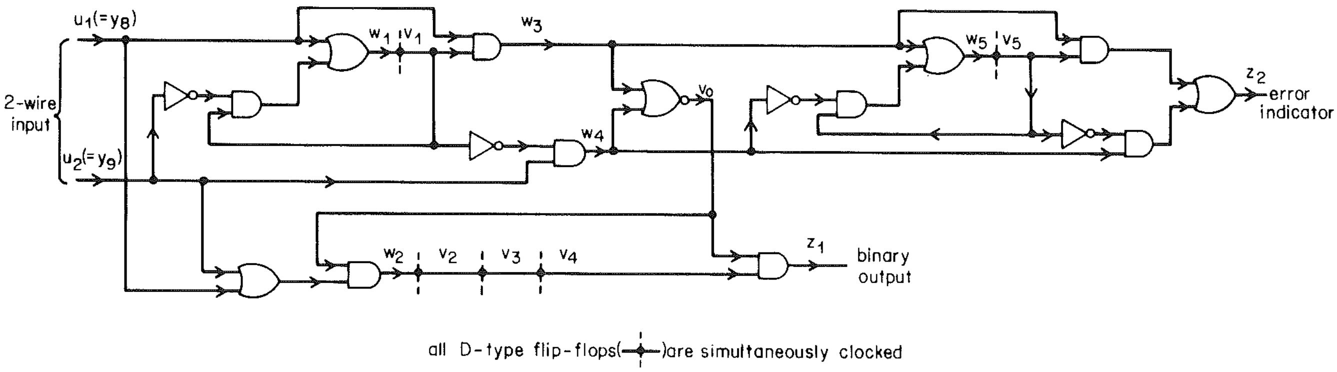


Fig. A2 - HDB3 Decoder and Error Monitor Logic

(ii) Receiver logic

The receiver (i.e. decoder and error monitor combination) logic is shown in Fig. A2. v_3 stores the sign of the previously received mark (v_3 = 1 for +, 0 for −). Hence w_3 = 1 for a positive (+) violation, w_4 = 0 for a negative (−) violation and v_0 = 1 if any violation occurs. When a violation is detected a zero is inserted into the output data stream at the 'present' and third previous symbol. v_5 stores the sign of the last previous violation; z_2 is a logical 1 if two successive violations are of the same polarity, thus indicating a transmission error.

(iii) Logic design details

The design philosophy entails synthesising explicitly only those variables used as the inputs to flip-flops. To obtain maximum clock rate, a given signal is allowed to pass through at most one gate between the output of one register and the input to another; this minimises the signal propagation time. The availability of complex function gates in emitter-coupled logic allows the synthesis of each variable as a (Boolean) product of sums. Moreover, each flip-flop has a logical complement output available, obviating the need for inverters in the circuits.

The following functions were synthesised:

$$\overline{y}_1 = (x_1 + x_2 + x_3).\overline{x}_0$$

$$\overline{y}_4 = (x_0 + x_1 + x_2 + x_3).(x_0 + \overline{x}_4).(\overline{x}_0 + x_4)$$

$$\overline{y}_5 = (\overline{x}_7 + \overline{x}_5 + \overline{x}_6).(\overline{x}_7 + x_5 + x_6).$$
$$.(x_7 + \overline{x}_5 + x_6).(x_7 + x_5 + \overline{x}_6)$$

$$\overline{y}_6 = (x_0 + x_1 + x_2 + \overline{x}_4).\overline{x}_3$$

$$\overline{y}_7 = x_0 + x_1 + x_2 + x_3$$

$$\overline{y}_8 = \overline{x}_6 + \overline{x}_5$$

$$\overline{y}_9 = \overline{x}_6 + x_5$$

$$\overline{w}_1 = \overline{u}_1.(u_2 + v_1)$$

$$\overline{w}_2 = (\overline{u}_1 + u_2 + v_1).(u_1 + \overline{u}_2 + \overline{v}_1)$$

$$\overline{w}_3 = (\overline{u}_1 + \overline{v}_1).(u_1 + \overline{v}_5).(v_1 + \overline{v}_5)$$

$$z_1 = v_4.(\overline{u}_1 + \overline{v}_1).(\overline{u}_2 + \overline{v}_2)$$

$$\overline{z}_2 = (v_5 + v_1 + \overline{u}_2).(\overline{v}_5 + \overline{v}_1 + u_1)$$

The registers forming x_7 and x_6 (from y_7 and y_6) in the encoder are instrumentally necessary to avoid the signal $x_3 \rightarrow y_7 \rightarrow y_5$ passing through two gates in succession.

The three level coded signal output is obtained by an analogue subtraction of the signal y_9 from y_8; similarly, at the receiver input u_1 and u_2 are obtained by level-detecting the incoming (coded) signal.

CLA/AMM

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey